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Effects of a Tanker Accident and an Oil Blowout in Bristol Bay, Alaska, on Returning Adult Sockeye Salmon (*Oncorhynchus nerka*)—A Simulation Study*

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ABSTRACT

The effects of a tanker accident releasing 34 000 tons of diesel fuel and a blowout releasing 3000 t/day of crude oil on adult sockeye salmon returning through Bristol Bay, Alaska, were simulated. Parameters in the simulation were chosen to maximize possible effects of the oil. Mortalities from the tanker accident were predicted to range from 2% to 18% of the adults passing through the spill area or 1% to 5% of the total returning population. From 3% to 7% of the adults surviving migration through the spill area, or 1% to 2% of the total population, could be tainted at or above 0·6 ppm of hydrocarbons in the flesh. As many as 30% of the adults returning to fishing grounds closest to the spill area could be tainted. Effects of the blowout on returning salmon were less severe than those of the tanker accident, with mortalities reaching a maximum of 0·2% of the adults passing through the area of the blowout, and no tainting predicted above 0·6 ppm.

INTRODUCTION

The most valuable concentrations of Pacific salmon (*Oncorhynchus* spp.) in Alaska pass through Bristol Bay on their way to and from the Bering Sea and Pacific Ocean (Fig. 1). Sockeye salmon (*O. nerka*) are the most abundant

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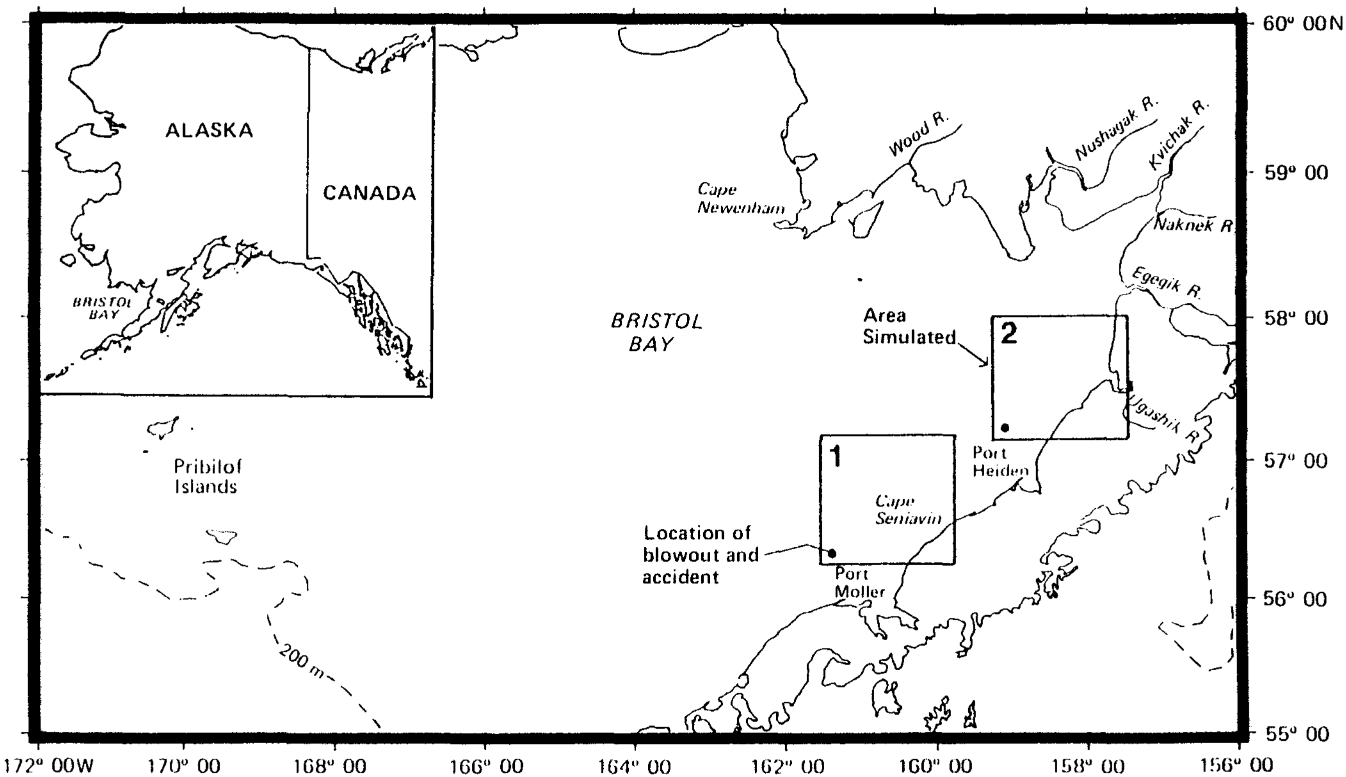


Fig. 1. Bristol Bay, Alaska, and the location of the hypothetical oil spill scenarios.

of the Bristol Bay salmon comprising 89% of the adult returns since 1951 (Rogers, 1977). In 1983 there was a record inshore return of 45 million adult sockeye salmon (Poe & Rogers, 1985).

Sales of oil exploration rights in the southwestern Bristol Bay have been proposed for several years and the first sale was scheduled for January 1986. There has been, and will continue to be, concern over potential conflicts between the commercial fisheries and oil development: indeed, the State of Alaska proposes a 10-year moratorium on oil exploration until adequate information on the fishery resources is available. This study was funded through the Outer Continental Shelf Environmental Assessment Program (OCSEAP) to investigate the potential interaction between oil development and the valuable sockeye salmon resources of Bristol Bay, and to summarize the information available to date for assessing those interactions. Simulations were developed to assess potential short-term impacts of an oil spill and an oil blowout; neither long-term effects of these catastrophic events nor effects of potential long-term environmental degradation were included.

BRISTOL BAY SOCKEYE SALMON

Generalized life cycle

Life histories of Bristol Bay sockeye salmon are variable but can be generalized as follows from Royce *et al.* (1968). Original citations from Royce *et al.* will not be given here.

In August and September the adult sockeye salmon spawn in the extensive Bristol Bay river systems. Fry emerge the following June and move to a lake where they spend one or two winters. They migrate out of the lakes after the breakup of lake ice, mainly in June, into Bristol Bay (Fig. 1). During the first few months at sea they migrate through Bristol Bay, remaining within 54 km of the southern shore, and feed on larval fish and euphausiids (Straty, 1974). It is thought that they stay in the Bering Sea until autumn, reaching the western Bering Sea before proceeding southwards into the North Pacific Ocean and the Subarctic current. In the next spring and summer, the beginning of their second ocean year, the young sockeye salmon commence their characteristic summer migration with the Alaska stream along the south side of the Aleutian Islands. The salmon repeat this elongated east–west course, which extends from about longitude 165°E to 140°W, once or twice before returning to the estuaries of their natal rivers in Bristol Bay.

The above generalized life history description conceals the variability within the Bristol Bay salmon; for example, sockeye salmon, which subsequently returned to Bristol Bay, have been identified from 2200 km west of Bristol Bay (off the Kamchatka Peninsula) to 2200 km to the east (in the central Gulf of Alaska) as late as May 1 in their final year. Despite this widespread distribution the return timing is finely delimited.

Adult migrations through Bristol Bay

Adult sockeye salmon return to Bristol Bay over a narrow period of time with 80% of the run passing the fishery over 12·9 days (SD 1·58 days) from 1956 to 1976 (Burgner, 1980). The mean time of return over the same period was July 4 (extremes June 28–July 10; SD 2·92 days). Adult sockeye were not caught inshore with exploratory fishing, at least until east of Cape Seniavin (Straty, 1975). These data corroborate conclusions of Hartt (1966; cited by Straty, 1975) that adult sockeye bound for Bristol Bay from the Pacific Ocean traveled north into the Bering Sea before turning east into Bristol Bay.

Offshore distribution of adult salmon within the Port Moller/Port Heiden area has been studied using exploratory gillnet fishing (Straty, 1975). I have reanalyzed the data taken on a transect from Port Moller to Cape Newenham (160°30′W) in 1965 and 1966 (12 sets), and on a transect from Cape Seniavin to Cape Newenham in 1939 (16 sets). Catch data were first recorded as the proportion of the total catch caught on each survey that was

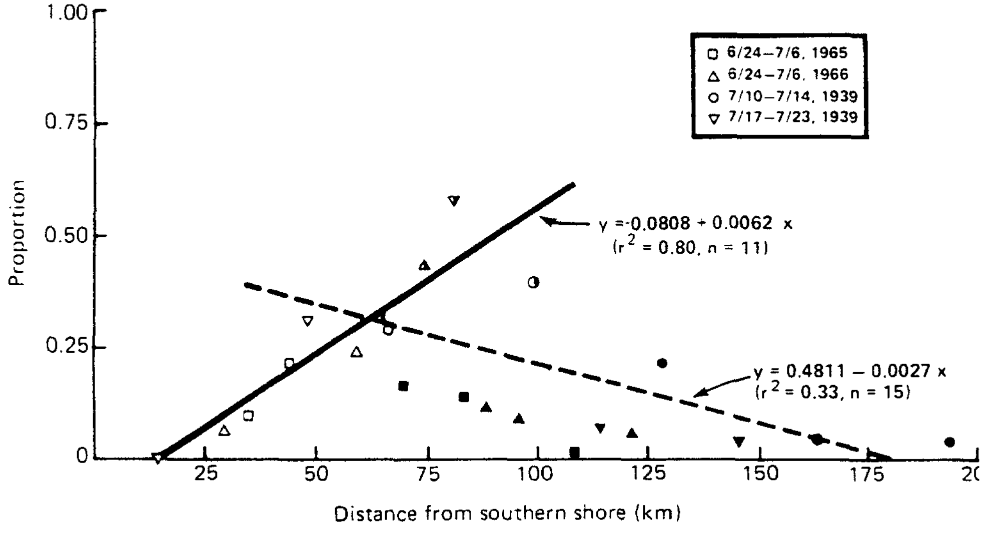


Fig. 2. Proportions of sockeye salmon caught at varying distances from shore during exploratory gillnet surveys in Bristol Bay. Shaded symbols indicate catches to the north of the mode for each survey; half shading is the mode. Regressions are fitted to the data to the north or the south of the mode. Data from Straty (1975).

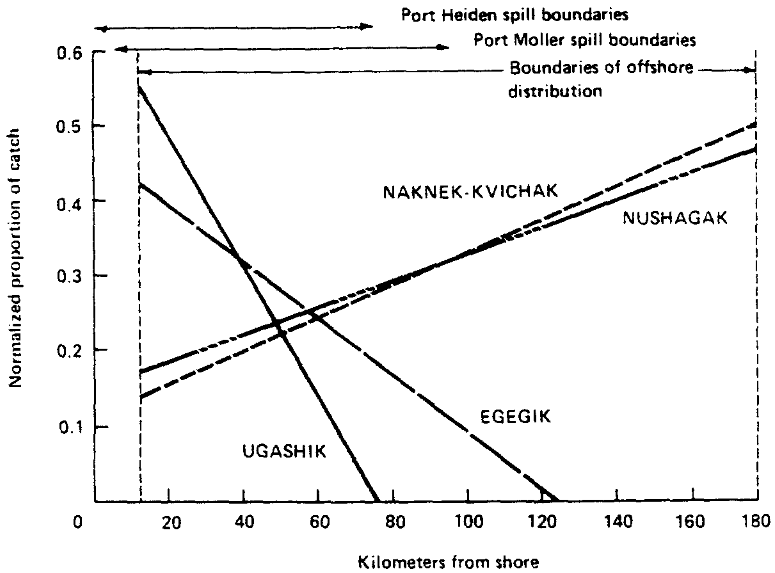


Fig. 3. Proportion of adult sockeye salmon by river caught in exploratory gillnet fishing between Port Moller and Port Heiden, Bristol Bay, that were caught at varying distances from shore. Data from Straty (1975).

caught on each transect. These proportions were then plotted against the distance from shore of each transect (Fig. 2). The distribution of catch with distance from shore was, in general, unimodal. The mode for each survey of each transect (with the exception of that off Cape Seniavin in late June 1939, which was multimodal) was determined and the data divided into two sets: one to the north (offshore) and one to the south (inshore) of the mode. Regressions were run on the two data sets. These two regressions intersected at 63 km offshore (Fig. 2), indicating the average location for the center of the distribution. Similarly, the intercepts on the abscissa at 13 and 178 km indicate the mean inshore and offshore limits of the distribution. The proportions of the tagged fish at each distance from shore that returned to each river were calculated, normalized over river and plotted (Fig. 3). Tagged fish returning to the rivers closest to the point of tagging, the Ugashik and Egegik, were found closer to shore than the fish returning to the more distant rivers.

OIL SPILL CHARACTERISTICS

Locations along the principal migratory route of returning adult sockeye salmon, one 30 km seaward of Port Moller and one 30 km seaward of Port Heiden, were selected by the Outer Continental Shelf Environmental

Assessment Program (OCSEAP) (Fig. 1). Hypothetical oil spill scenarios, an instantaneous spill of 34 000 tons of automotive diesel fuel (No. 2) and a well blowout of 42 000 tons of Prudhoe Bay crude oil discharged at approximately 3000 t/day for 15 days were simulated. Oil distribution in the water, which includes oil in solution as well as particulate oil, was computed by Liu & Leendertse (1985). The most frequent local wind direction was used in these calculations. Values for wind strength and tidal action which maximized the amount of oil entering the water column were used.

The volume of oil spilled in the hypothetical tanker accident is exceeded by the spill of the *Amoco Cadiz* (about 230 000 tons) and the *Ixtoc I* well blowout (about 300 000 tons); both of these accidents involved crude petroleum. This hypothetical spill far exceeds any past spills of middle or heavy distillate petroleum fuels. Total volume of the blowout is comparable to the *Ekofisk Bravo* blowout (about 20 000 tons), but is considerably less than that from the *Ixtoc I* blowout.

EFFECTS OF OIL ON SALMON

Avoidance

The few studies of avoidance of pollutants by adult salmon have been conducted in the field. Westerberg (1983*a*) observed retrograde movement by ultrasonically tagged adult Atlantic salmon released in a polluted branch of the Lule estuary (dredging and effluents from a steelworks and a coke-oven plant), whereas tagged adults released in an unpolluted branch of the same estuary showed a slow, but upstream, progress. Perhaps the best study to date on the effects of pollutants on avoidance by salmonids is that of Weber *et al.* (1981), who measured the avoidance of returning adult Pacific salmon (99% coho salmon) to parallel fish ladders on their natal stream. Avoidance to the ladder polluted with a close approximation to the WSF of Prudhoe Bay crude reached 50% when the concentration reached 3·2 mg/liter at the top and middle of the ladder. The regression of per cent of adults ascending the polluted ladder on the concentration of hydrocarbons was $Y = 50{\cdot}11 - 8{\cdot}04X$ (correlation coefficient = 0·92).

Rates of uptake and depuration

The concentration and subsequent elimination, or depuration, of hydrocarbons from the salmon is of interest for two reasons: tainting from hydrocarbons within the muscle and lethal or non-lethal stress resulting from uptake into other organs; for example, the liver and gall bladder. Accumulation rate is not the same for the muscles and organs; maximum levels of naphthalenes were found in the liver of adult Atlantic salmon exposed to approximately 0·04–0·05 ppm crude oil in a flow-through vessel after 7 h (at 42 ppm or 1000 times external concentration), while the maximum levels in the muscle were after 6–8 days (9·5 ppm or ten times external concentration; Brandl *et al.*, 1976). Organoleptic analysis also indicated that maximum muscle tainting occurred at 6–8 days; no mortalities occurred. Depuration began at an earlier stage in the liver, reducing naphthalene levels to 2–3 ppm after 6–8 days, the time of maximum levels in the muscle, which, in turn, depurated to 0·02 ppm after 39 days. I emphasize that during depuration the salmon were still exposed to the flow-through water polluted at 0·04–0·05 ppm, although the concentrations of the more volatile hydrocarbons had decreased. Roubal *et al.* (1978) exposed juvenile coho salmon to 0·9–1·0 ppm of the WSF of Prudhoe Bay crude in flow-through containers over 6 weeks. Testing the fish after 2, 3, 5 and 6 weeks indicated maximum levels in the muscle at 5 weeks (10·35 ± 1·83 ppm, overall bioconcentration 10, bioconcentration of naphthalenes 117). No hydrocarbons were detected in the muscle after 1 week depuration in clean water. The difference in times of maximum bioconcentration between the two studies may be due to the loss of the more volatile aromatics in the Brandl *et al.* (1976) experiment.

None of the above studies addressed the uptake pathways for the oil into the flesh; however, NAS (1975) concluded that for animals with respiratory surfaces in contact with seawater the interface between animal and water may be the most important avenue for uptake and loss of hydrocarbons; this avenue supersedes any food web magnification. Morrow (1974) found no significant mortalities of young coho and sockeye salmon force fed with 1 g oil per 100 g body weight per day. The relative lack of importance of feeding to oil uptake may be especially applicable to salmon; coho salmon smolts were reported to stop feeding at 0·32 ppm of Cook Inlet WSF (Thorsteinson & Thorsteinson, 1982).

Oil-induced mortalities

The sensitivity of salmon to oil decreases during their exposure as the detoxification or excretion rate increases with increasing activity of the enzymes in the liver that metabolize aromatic hydrocarbons (Moles *et al.*, 1981). Other works cited by these authors have shown that there is an increase in aryl hydrocarbon hydroxylase in coho salmon after their exposure to crude oil or aromatic hydrocarbons. Rice *et al.* (1977) speculate that there is a large energy requirement from initial exposure to oil to synthesize the large quantities of enzymes needed to metabolize hydrocarbons into excretable forms. If the fish are not overwhelmed by this initial exposure, their increased enzyme activity enables them to rid themselves of the toxic compounds.

Thus, although experimental results are often recorded as the concentration necessary to produce 50% mortalities after 96 h (96 h median tolerance limit, or TLM), the majority of mortalities occur within the first 12 or 24 h (Cardwell, 1973; Moles *et al.*, 1979, 1981; Rice *et al.*, 1977). Less than 1% of the mortalities of coho fry exposed to various concentrations of toluenes and naphthalenes occurred after 96 h (Moles *et al.*, 1981).

Several estimates of the 96-h TLM of juvenile salmon exposed to oil are available in the literature, with variability between the studies at least partly accounted for by the different analytical methods. I am not aware of any studies on oil-induced mortalities for adult salmon. Since most mortalities occur during the first 24 h of exposure, a distinction between flow-through and static experiments (where evaporation of the lighter hydrocarbons occurs) does not seem necessary. Estimates of the 96-h TLM for sockeye salmon smolts exposed to crude oil vary from 1·0 to 4·0 ppm (Moles *et al.*, 1979). Estimates for other species of young Pacific salmon exposed to crude oil range from 1·2 to 11·0 ppm (Rice *et al.*, 1975, 1977; Moles *et al.*, 1979, 1981, 1983; Moles, 1980). Dr Adam Moles of the Auke Bay Laboratory, NOAA, provided me with data on mortalities of outmigrant sockeye salmon exposed to varying levels of Prudhoe Bay crude oil and Fuel Oil No. 2 in seawater. These data are reproduced in Fig. 4, where simple linear regressions have been fitted to the data which were highly linear (r^2's = 0·99) after concentrations which exceeded the limits of response were excluded. Mortalities were approximately an order of magnitude higher for salmon exposed to Fuel Oil No. 2 compared with fish exposed to the same concentration of Prudhoe Bay crude.

Tainting by petroleum products

Reports of tainting have followed spills of diesel fuel. A tanker spill of 2200 tons of diesel oil near Finnsnes, northern Norway, was spread by wind and currents in the Gisund, a narrow straight. In the ensuing two months fishermen reported the smell and taste of oil in cod, saithe, haddock, herring, flounder, sea trout and salmon. Two months after the spill sampled fish were tasted by a trained taste panel and the flesh analyzed for hydrocarbons by gas chromatography and mass spectrometry. Concentrations of hydrocarbons were still in the order of 0·15–0·20 ppm in the liver of the cod even though the components of diesel oil were no longer present in the samples of water and sediments taken at the site (Palmork & Wilhelmsen, 1974; cited by GESAMP, 1977). The degree of tainting following exposure to petroleum products depends on the type of petroleum

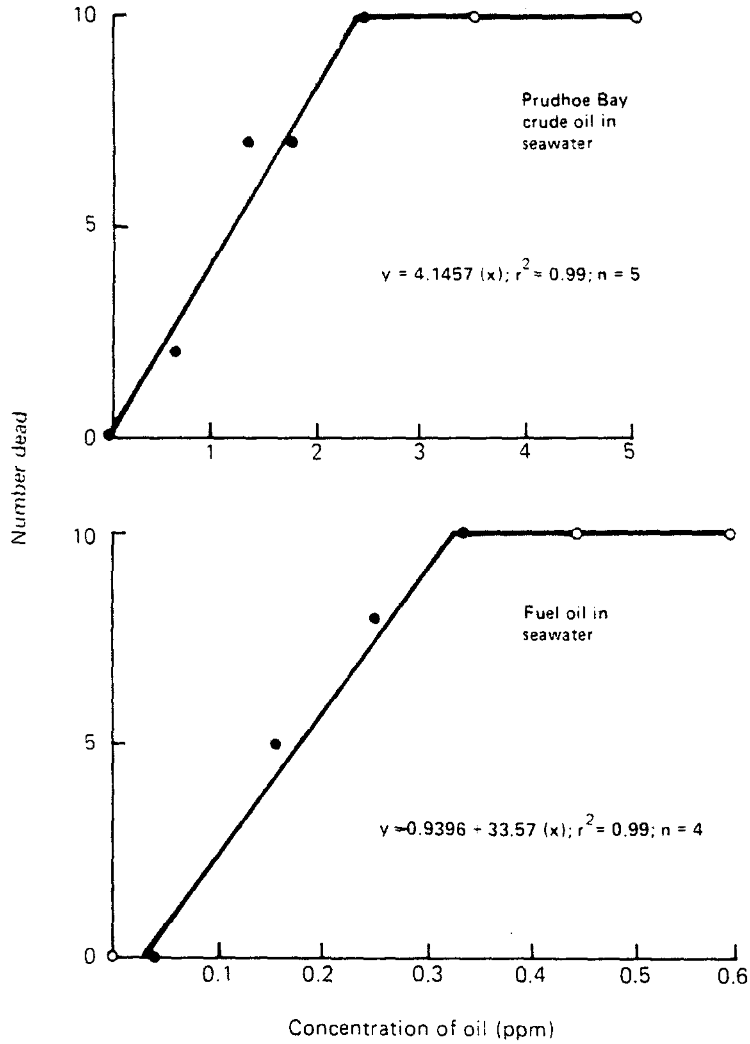


Fig. 4. Number of sockeye salmon smolts dying (out of 10) following exposure to oil in static seawater for 96 h. Data from Adam Moles, Auke Bay Laboratory, NOAA. (Regressions used shaded data only.)

involved. Thus Kerkhoff (1974; cited by GESAMP, 1977) reported that the middle distillate fraction of crude oil, e.g. diesel fuel, contains many of the odorous components present in the crude, and whilst diesel oil in water can be detected nasally at 0·0005 ppm, fuel and crude oils can only be detected at 0·1 to 0·5 ppm (Martin, 1970; cited by GESAMP, 1977).

A well-executed study designed to simulate the effects of an oil spill weathered for several days on entrained fish was conducted by Brandl *et al.* (1976). Fifty salmon (100 g) were kept in a flow-through vessel (turnover rate

30 min) for 68 days, during which time they were not fed. Tainting was first observed after 4 days' exposure to the water contaminated with an average 0·04 to 0·05 ppm hydrocarbon. The tainting became obvious after 6 days, had returned to the 4-day level after 13 days and, after 30 days, was identical with the controls. The only components of significant concentration found in the fish were naphthalenes and benzene compounds, the latter being too volatile for quantitative determination; the authors suggest that the benzenes and benzene compounds were present at levels roughly equivalent to those of the naphthalenes. Naphthalene concentration reached a maximum of 0·5 ppm after 6 to 8 days in salmon muscle (bioconcentration of 10) and depurated to 0·03 ppm after 39 days. The salmon liver had higher concentrations of naphthalenes, reaching a maximum of 42 ppm (bioconcentration of 1000) after 7 h, decreasing to 2 to 3 ppm after 6–8 days. The authors conclude that, therefore, a concentration of 0·3 ppm naphthalenes is necessary for tainting to be observed.

The 0·3 ppm tainting threshold level suggested by Brandl *et al.* (1976) is an order of magnitude lower than the other available estimates as reviewed by GESAMP (1977), which range from 5 ppm of kerosene in spiked tissue from muscles (Kerkhoff, 1974) to 4 to 12 ppm of diesel oil components in lobster (Paradis & Ackman, 1975) to 10 to 30 ppm of crude oil in spiked tissue (Whittle & Mackie, 1975).

The importance of tainting to commercial fisheries following exposure of the resource to hydrocarbons depends on the severity of the contamination itself, the rate of uptake and depuration, and the diffusion of tainted fish through a larger population. Thus, a kerosene-like taint in the sea mullet (*Mugil cephalus*), thought to be due to their exposure to refinery effluents, resulted in the condemnation of 78 short tons near Brisbane (Grant, 1969; cited by GESAMP, 1977); the tainted fish were spread over 160 km of coast and were mixed with untainted fish, resulting in the condemnation of entire catches (Connell, 1974; cited by GESAMP, 1977).

OVERVIEW OF SIMULATION

Two stages were used to simulate the maximum effects of a specific oil spill scenario on the migrating salmon. In the first stage the maximum proportion of the Bristol Bay sockeye salmon that could be at the longitude of the spill area over a 10-day period is estimated, and in the second stage the proportion of the population passing through the spill area in 10 days that would be affected by that spill is simulated. Together with data on the inshore/offshore distribution of the salmon, these two simulations estimate the maximum impact of a specific oil spill scenario. Parameters used in the simulation tend towards maximizing potential effects of the oil spill when data are ambiguous.

Effects of an oil spill on migrating salmon

A general description of the simulation follows and is illustrated in Fig. 5. Fish, or schools of fish, are assigned to the squares in the grid in proportion to their historic probability of occurrence, with the maximum probability receiving five fish for each square. Each fish is recorded individually and will be treated individually throughout the simulation. Final output is as the statistical means and accompanying variances of these fish.

For each fish in each timestep a working grid is set up composed of the eight adjacent squares. Values for probabilities of occurrence and oil concentrations are transferred from the main grid to those working grids at each timestep. The timestep in the simulation is set to equal the time taken for a fish to move to an adjacent square (i.e. the length of an individual square (2 km) divided by the migration speed in km/h). At each timestep the fish must move to an adjacent square that is selected based on the product of the historical probabilities of occurrence, the probabilities of migration in the direction of each square and the probabilities of avoidance of the ambient oil concentration (if any) in each square.

Two parameters are required in this simulation to compute the probability of migration in any direction—the preferred migration direction (*ANGLE*) and the spread around this preferred direction. Two options are available to simulate the spread around the preferred migration direction. The first option, direct migration, permits no spread around the preferred direction, and consequently no avoidance of an oil spill. The second option assigns probabilities of migration (*COMPROB*) in any direction of the compass (*COMPAS*) from the following equation:

$$COMPROB = ((180 - |COMPAS - ANGLE|)/180)^{DPOWER};\ \text{min } 0{\cdot}01 \quad (1)$$

where *DPOWER* controls the degree of spread around *ANGLE*.

There are insufficient data available to describe the small-scale coastal migration patterns of Pacific salmon. Available data indicate that the migration route of returning adult salmon would not be adequately described by a straight line (Ichihara & Nakamura, 1982; Westerberg, 1983*b*). Adult sockeye salmon migrate approximately parallel to the southeastern Bristol Bay shoreline with a mean migration rate of 0·9 body lengths (BL)/s. Many combinations of swimming speed and diffusion could simulate these migration characteristics; in this simulation I have defined only the upper and lower limits of swimming speed.

The lower limit of swimming speed would be 0·9 BL/s under direct

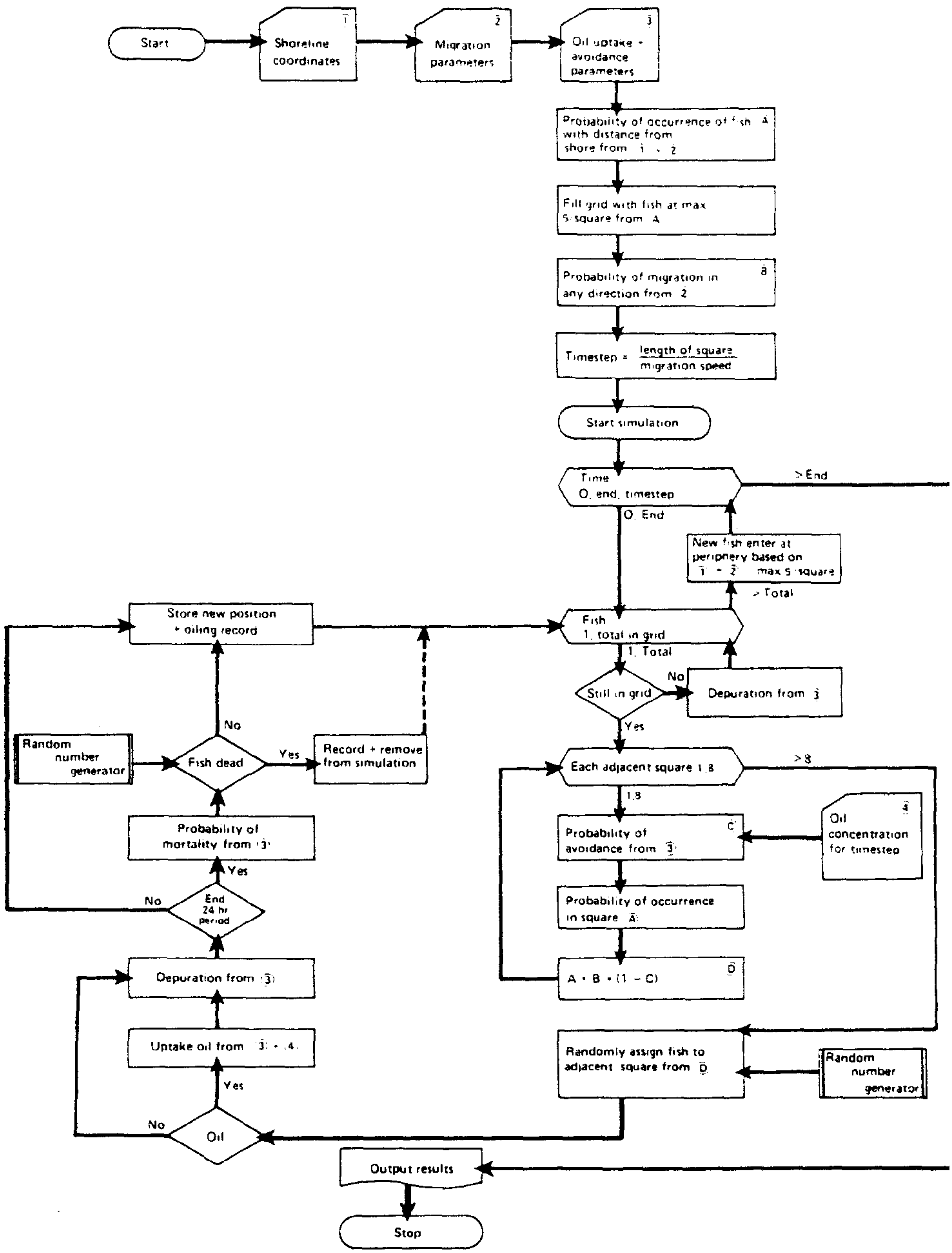


Fig. 5. Flow chart of processes involved in simulating the movement of sockeye salmon through an oil spill in Bristol Bay.

migration when the swimming speed would equal the mean migration rate. Under this condition no avoidance of the spill would be possible. An upper limit to swimming speed was defined from the theoretical studies of Weihs (1975), Trump & Leggett (1980) and Wakeman & Wohlschlag (1981), which suggest a maximum likely swimming speed of 2 BL/s. In combination with a gradient of probabilities (*DPOWER*) set at 1·3 this swimming speed of 2 BL/s will produce the desired mean migration rate of 0·9 BL/s. Under the above assumptions this combination will result in the maximum possible avoidance of the spill in this simulation.

The historical probability of occurrence of the salmon in the area is not equal in all possible directions of migration. The derivation of these historical probabilities is based on the distance of each square from the shoreline, since historical catch data suggest that the abundance of adults increases from zero at 13 km to a maximum at 64 km offshore, thereafter dropping to zero at 178 km (Fig. 2; Straty, 1975).

Finally, the presence of oil in any of the adjacent squares would affect the migration direction. The probability of avoidance (*AVOID*) of that level of crude (*OIL*) is determined from regression functions fitted to the data of Weber *et al.* (1981):

$$P(AVOID) = 0{\cdot}16 * OIL;\ \max\ 0{\cdot}90 \qquad (2)$$

Maximum avoidance probability is limited to 0·90 because the avoidance response of individual fish is variable (Birtwell & Harbo, 1980; Bohle, 1982), and Weber *et al.* (1981) provide no data on avoidance probabilities above 0·75.

No comparable data are available for the potential avoidance of concentrations of fuel oil. I assume that the sevenfold greater sensitivity to fuel oil compared to crude oil as measured by the probabilities of mortality (described later) can be transferred directly to the probabilities of avoidance.

The probability distributions for migration, detection, historical probability of occurrence and avoidance of oil are multiplied together and the product normalized to total 1·0. Based on this probability distribution the fish is randomly assigned to one of the adjacent squares. If the square to which the fish has been moved contains oil, then this oil is taken up into the flesh in a prescribed manner and in all instances any existing oil in the flesh is depurated. Uptake of oil and its depuration are based on the experiments of Brandl *et al.* (1976). Uptake of oil to the flesh over the course of a single timestep is equal to the product of the external concentration and the bioconcentration rate per timestep. A bioconcentration rate of 3·0 is suitable to simulate the results of Brandl *et al.* (1976). This bioconcentration rate is increased to 21·0 for fuel oil, the justification for this adjustment having been presented previously. Depuration is set to increase by 3% per day from zero on the day of first contact with oil to a maximum of 90% loss of oil per day after 30 days, simulating the increase in appropriate enzyme activity by the affected fish. Together the expressions for uptake and depuration produce maximum concentrations of oil in the flesh after 7 days, with maximum bioconcentrations of 11 and 77 for crude and fuel oil, respectively. Internal concentrations of oil in the flesh decrease to 50% of the original ambient levels after approximately 30 days. Any fish with an internal flesh concentration greater than, or equal to, 0·6 ppm is considered tainted.

In this simulation I represent oil-induced mortalities as a direct function of the exposure history of the fish rather than attempting to simulate the uptake of oil to sensitive organs and the internal lethal levels. Mean exposure concentration over the previous 24-h period is computed and the probability of mortality at this mean exposure level computed according to functions derived from Moles (unpublished data):

$$\textit{Fuel oil:} \quad \mathrm{P}(MORTALITY) = 0{\cdot}093\,96 + 3{\cdot}357(XCON) \tag{3}$$

$$\textit{Crude oil:} \quad \mathrm{P}(MORTALITY) = 0{\cdot}414\,57(XCON) \tag{4}$$

where $XCON$ is the mean external concentration of oil in ppm experienced by the fish over the previous 24 h. Two constraints are placed on these calculations to preserve independence in the mortality probabilities between 24-h periods. First, the probability of mortality is computed only at the end of distinct 24-h periods (i.e. at 24, 48, ..., 240 h) and, secondly, the probability of mortality is computed only if the current mean exposure concentration is greater than that immediately pre-dating it.

This simulation of oil-induced mortalities completes the simulation for the individual fish in this timestep, and the simulation now proceeds to the next fish (Fig. 5). When the migration simulations take a fish outside of the main grid, the fish is flagged and, in future timesteps, undergoes depuration only. Perimeter squares of the grid are replenished at the end of each timestep so as to equal the maximum number indicated by their associated historical probability of occurrence. The simulation is now ready to proceed to the next timestep.

RESULTS

Presence in area

Historical data indicate the return of adults to Bristol Bay as monitored by the fisheries to be well defined. From 1956 to 1976, 80% of the run passed the fishery over a 12·9-day period (SD 1·58 days (Burgner, 1980)). The mean time of return over the same period was July 4 (extremes June 28–July 10). Mean migration rate of the returning adults is approximately 50 km/day; thus, essentially all of the returning run would pass the latitude of the blowout grid (100 km long) over the 20-day simulation. Over the 10-day simulation for the tanker accident, adults spread out over 568 km (10 days at 50 km/day, plus the length of the grid) would pass the latitude of the 68-km long grid. Since 80% of the run is spread out over 12·9 days, or at 50 km day over 645 km, and assuming a normal distribution (SE – 508 km), a maximum 74% of the run would pass the latitude of the 68-km long grid in a 10-day period.

The actual proportion of adults passsing through the grids will be determined by the offshore distribution in addition to the longshore distribution. Offshore boundaries of all four grids are inside the estimated offshore extent of the adults' distribution and thus only a proportion of the total population will pass through the grids (Table 1).

TABLE 1
Dimensions and Boundaries of Simulation Grids and Estimates of the Per Cent of the Total Migrants Passing within the Inshore and Offshore Boundaries of these Grids, and the Per Cent of the Total Population Passing Through Grids in the 10-day Period

Area	*Spill scenario*	*Grid size (km)*	*Inshore boundary (km)*	*Offshore boundary (km)*	*Estimated per cent of population passing through grid*	
					Total	*10-day period*
Port Heiden	Tanker accident	64 × 68	0	74	36	27
	Blowout	100 × 100	0	95	51	51
Port Moller	Tanker accident	64 × 68	6	94	55	41
	Blowout	100 × 100	0	117	71	71

Oil spill scenarios

Avoidance of the fuel oil spill does occur (Figs 6a–6c) with the adults mostly moving around the offshore perimeter of the spill; however, their migration is so rapid that little (if any) concentration of numbers occurs. Avoidance of the crude oil blowout was virtually undetectable (Figs 7a–7c). Mortalities were highest for the fuel oil spill scenario at Port Heiden (3% to 18%) and lowest for the two crude oil blowout scenarios (0·1% to 0·2%) (Table 2). When extrapolated to the whole population these result in estimates of overall mortality from the tanker spill of 1% to 5% and overall tainting of 1% to 2%.

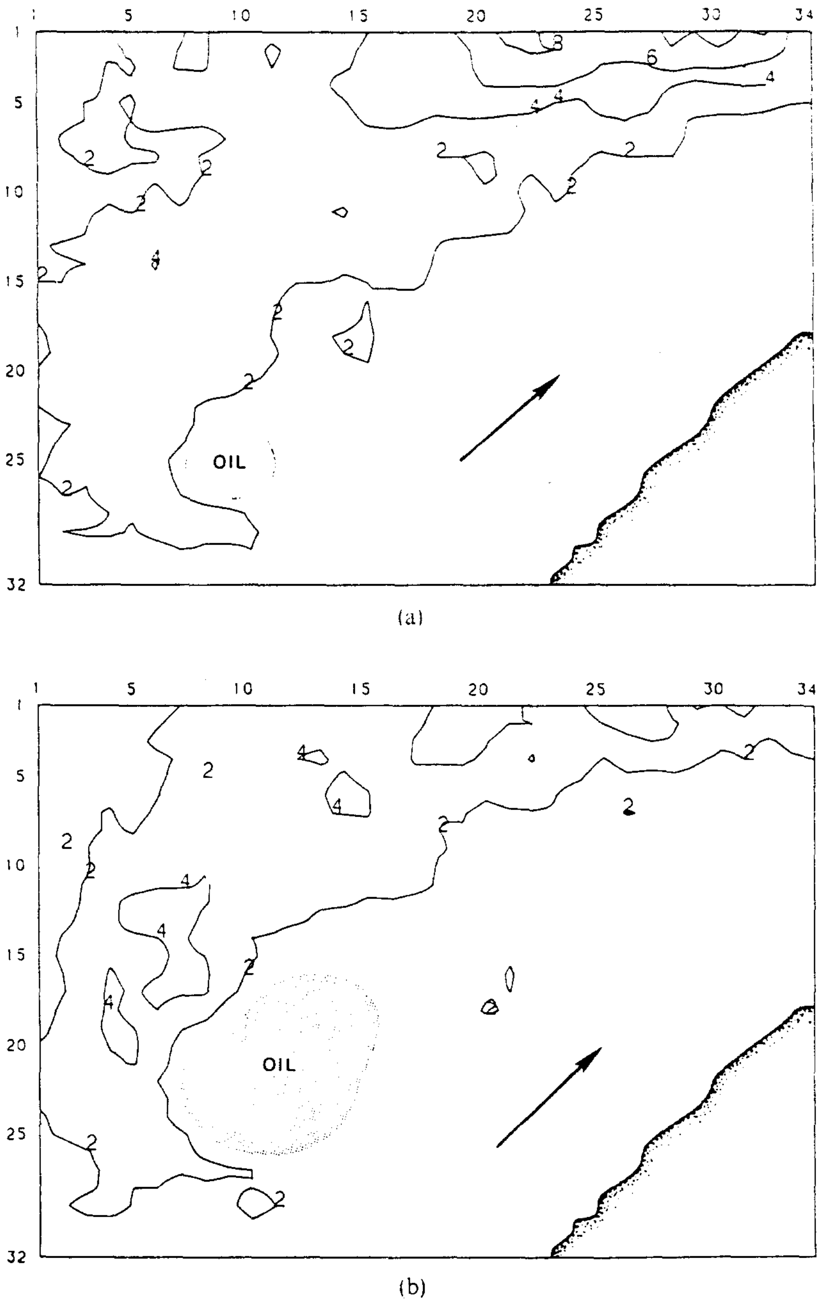
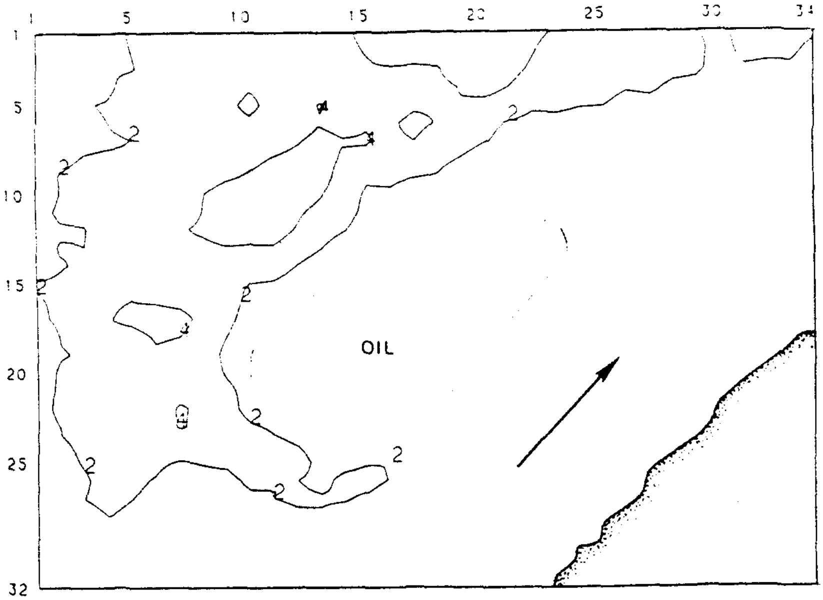


Fig. 6. Contour map of simulated concentrations of adult sockeye salmon migrating past a spill of 34 000 tons of diesel fuel off Port Heiden, Bristol Bay. Shaded area depicts oil concentrations greater than 1·0 ppm. (a) 48 h from start of spill. (b) 120 h from start of spill.



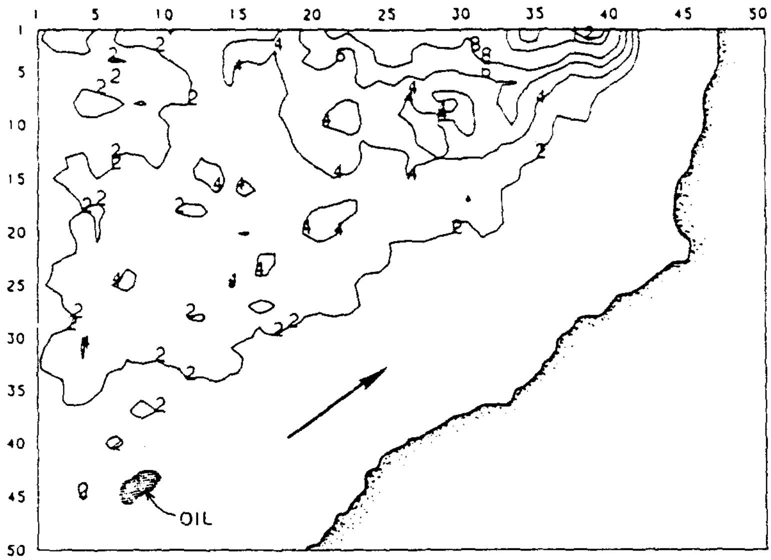
(c)

Fig. 6—*contd.* (c) 240 h from start of spill.

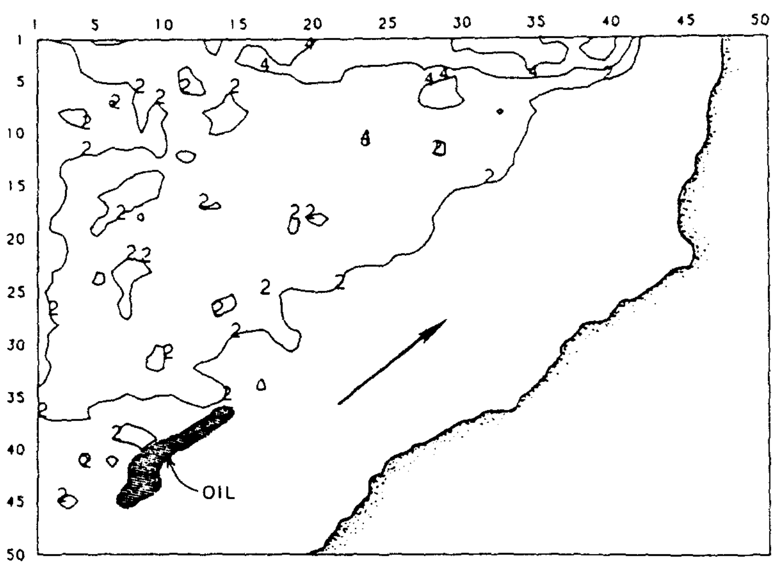
TABLE 2

Simulated Per Cent Mortalities and Per Cent Taintings of Sockeye Salmon Migrating Through the Oil Spill Grids Either Directly or with Avoidance of the Spill

Spill scenario	*Run time (h)*	*Fish migrating through area*		*Whole population*	
		Direct migration	*Migration with avoidance*	*Direct migration*	*Migration with avoidance*
		Per cent mortalities			
Port Heiden					
Tanker spill/fuel oil	240	17·6	3·2	4·8	0·9
Blowout/crude oil	480	0·2	0·1	0·1	0·1
Port Moller					
Tanker spill/fuel oil	240	11·6	2·1	4·8	0·9
Blowout/crude oil	480	0·2	0·1	0·1	0·1
		Per cent tainted above 0·6 ppm			
Port Heiden					
Tanker spill/fuel oil	240	7·1	3·1	1·9	0·8
Blowout/crude oil	480	0·0	0·0	0·0	0·0
Port Moller					
Tanker spill/fuel oil	240	5·0	2·6	2·1	1·1
Blowout/crude oil	480	0·0	0·0	0·0	0·0

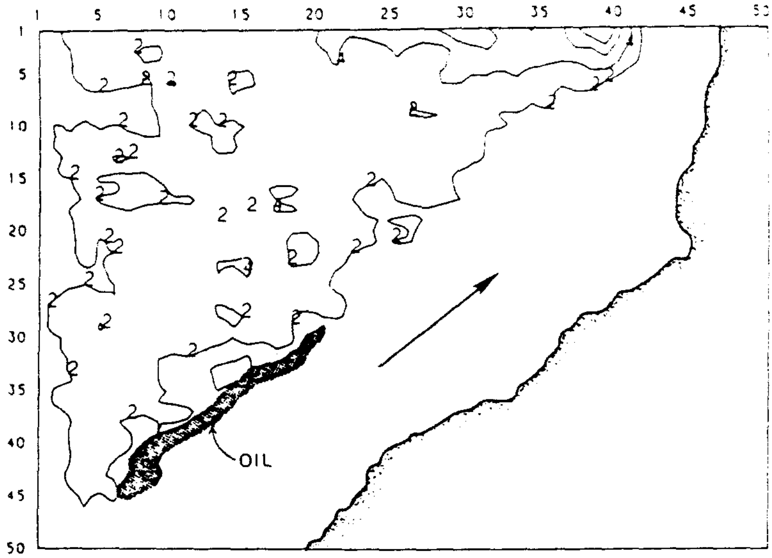


(a)



(b)

Fig. 7. Contour map of simulated concentrations of adult sockeye salmon migrating past a blowout of 3000 t/day of crude oil off Port Heiden, Bristol Bay. Shaded area depicts concentrations greater than 0·1 ppm. (a) 24 h from start of blowout. (b) 120 h from start of blowout.



(c)

Fig. 7—*contd.* (c) 480 h from start of blowout.

Levels of tainting at the fishing grounds

An important consideration for the adult salmon is to what extent tainted fish might arrive on the fishing grounds. While fish pass from the oil spill area to the fishing grounds depuration will occur, the degree of depuration depending on the distance (or time) travelled by the fish. Salmon tainted in the Port Heiden spill area would arrive at the fishing grounds of the Ugashik River the same day, but would (at 50 km/day) take 2–3 days to reach the Kvichak–Naknek rivers. To investigate the degree of tainting remaining in the migrants through the grid over time, the simulation was rerun allowing one day's migrants through the grid at a time and following their depuration over the subsequent 5 days. Results from the simulation of adults migrating directly through the Port Heiden spill are graphed in Fig. 8.

Tainting drops off rapidly once the adults enter uncontaminated water, with zero tainting being reached on days 4 to 6, or 3 to 5 days after the fish have left the contaminated area. Per cents tainted decrease at an increasing rate over time (Fig. 8).

An important factor affecting the proportion of adults reaching the fishing areas that are tainted is the proportion of the run from individual rivers that actually passes within the boundaries of the oil spill simulation grid. Earlier I proposed factors by which to reduce the simulation results to account for this (Table 1); however, these factors assumed no differential offshore distribution of adults from the four rivers. Data on the returns of 27

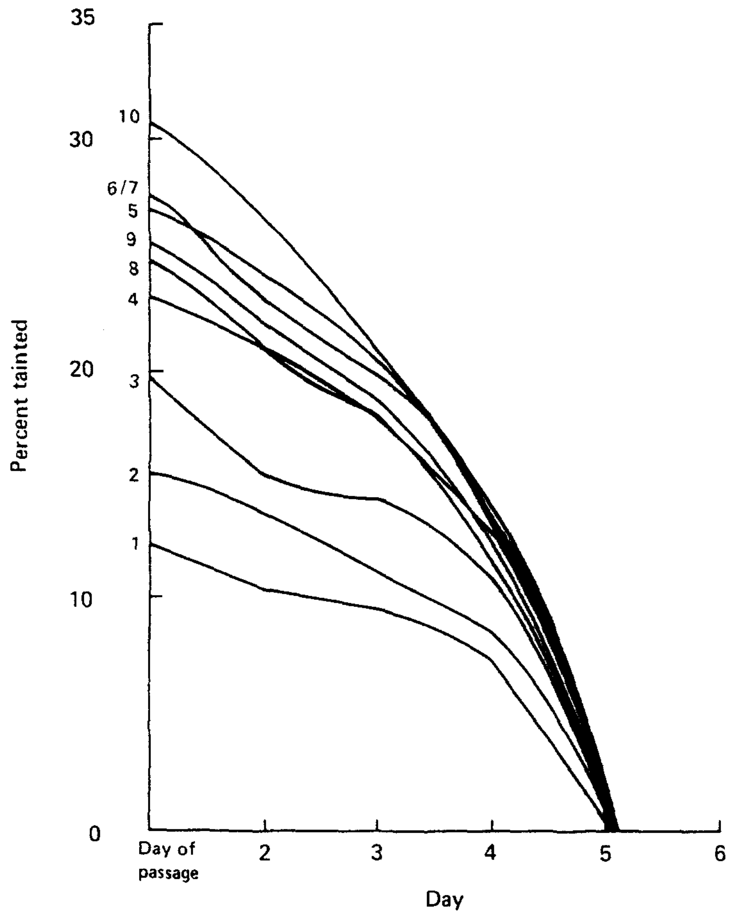


Fig. 8. Simulated per cent of adult sockeye salmon tainted after passing through a fuel oil spill off Port Heiden from days 1–10 of the spill, and the percentages remaining tainted over the next 5 days.

adults tagged and released at sites between Port Moller and Port Heiden suggest that the adults returning to different rivers are to be found at different distances from shore (Straty, 1975). I estimated from Fig. 3 the proportions of the adults from each river that would have passed within the boundaries of the oil spill simulation grids and obtained the following reduction factors:

	Ugashik	Egegik	Kvi-Nak	Nushagak
Port Heiden	1·0	0·8	0·3	0·3
Port Moller	1·0	0·9	0·4	0·4

These reduction factors were used to estimate the proportions of fish

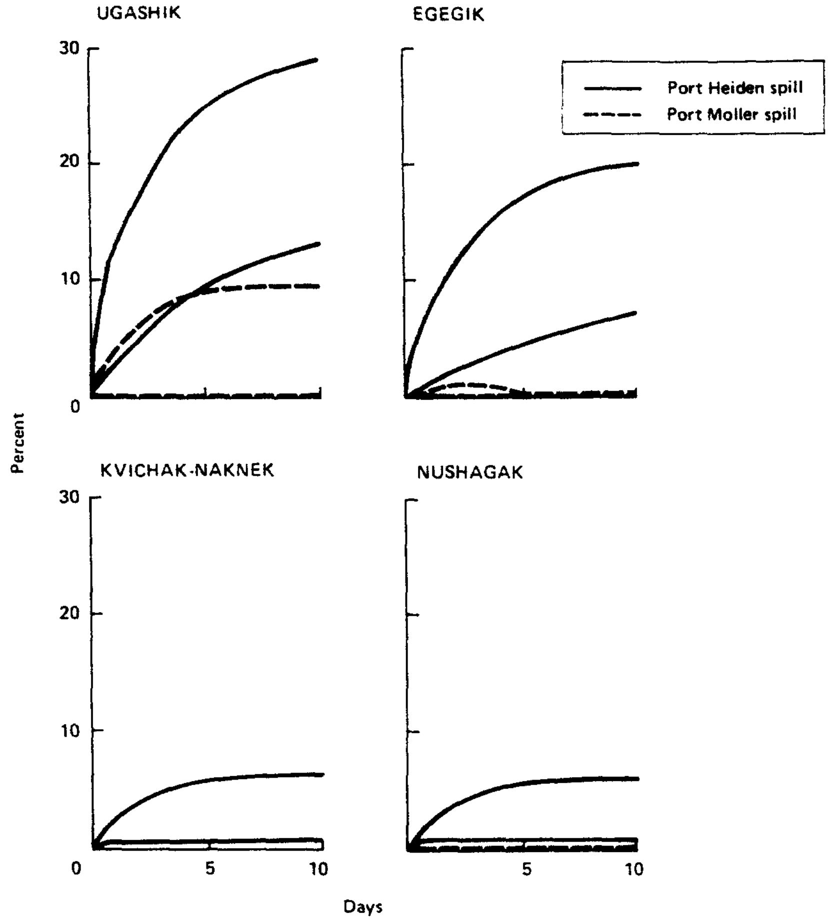


Fig. 9. Simulated proportions of adult sockeye salmon arriving on the fishing grounds in Bristol Bay that would be tainted after passing through a 34 000-ton spill of No. 2 fuel oil from day 1 to day 10 of that spill. The lower line in each instance is that obtained assuming some avoidance of that spill. There was no avoidance assumed in obtaining the upper line.

arriving daily on the fishing areas in Bristol Bay that would be tainted above 0·6 ppm. Results from their application are plotted in Fig. 9.

The greatest percentage of tainted fish will be found at the Ugashik River fishing areas, and are caused by a spill off Port Heiden. Per cents tainted might reach about 30%, although the higher values occur towards the end of the 10-day period and will be overestimated as no allowance has been made for evaporation of the lighter aromatic compounds which would cause some of the strongest taints. Greater reliance can be placed on the values for adults migrating through the spill area on day 1 and day 2, which indicate that approximately 15% of the adults reaching the Ugashik River fishing areas could be tainted.

DISCUSSION

The simulation presented here is, of necessity, an abstraction of the real events following an oil spill; further constraints were caused by a general lack of relevant data to estimate the required parameters. For this reason, the simulation was kept as simple as was consistent with the objectives of the study and the effects of the various parameters on the results can be qualitatively determined from the provided outputs. Parameters and algorithms were chosen to maximize any effects of oil on the fish: the lower bounds of effects provided by including a probability of avoidance of oil are again conservative as the avoidance algorithm operates only once in a timestep (1–2 h) and not continuously, as would be expected in the natural environment.

A Monte Carlo error analysis was performed on this simulation model with parameters for the Port Heiden area for a tanker spill. Two hundred runs were made with each input parameter simultaneously and randomly perturbed within a Gaussian probability distribution with a coefficient of variation of 15%. Results were obtained from the simulation at 48 h after the start of the spill and after a further 48 h in unpolluted waters. Multiple regressions were run on each output variable with all input parameters as independent variables (Table 3).

Effective swimming speed was influenced most heavily by the size of the fish and the assigned level of diffusion around the mean migration direction (a parameter for which empirical data are not directly available). Fortunately, however, swimming speed was not a dominant factor in determining numbers tainted or dead. The historical probability of occurrence in the locus of the spill area was a major determinant of numbers tainted and numbers dead, as were the hydrocarbon concentration at which tainting occurred and the rate of increase of depuration with time. Oil concentrations and fish size impacted both tainting and mortalities to a lesser degree. The results from this simulation appear highly specific to the scenario simulation, thus an oil spill at a different location could have very different effects.

Several features of the simulation require final emphasis. Avoidance, tainting and death are the only effects of oil contamination considered. Other potential effects not treated include reductions in visual acuity or chemoreception that would affect subsequent schooling, homing and spawning, as well as energy losses caused by cessation of feeding in contaminated waters, by avoidance of the spill or by a loss of directed migration on first contact with the spill. These effects could reduce the probability of survival from future stresses, and could seriously impact the adults which require large amounts of energy during upstream migration and spawning but are not feeding at the time.

TABLE 3
Multiple Regressions on Output Variables from 200 Run Monte Carlo Error Analysis

	Output variables					
	48 h after start of spill			*After 48 h in unpolluted water*		
	Swimming speed	*Number tainted*	*Number dead*	*Swimming speed*	*Number tainted*	*Number dead*
			Positive correlations[a]			
Input parameters	DPOWER blsec	prob3 oilup angle	PROB3 ppboil angle xcon dpower	DPOWER blsec	prob3 ppboil oilup	PROB3 ppboil angle xcon dpower
			Negative correlations			
	FISHSZ	TLEVEL fuelup avoid depinc fishsz	prob4 fishsz	FISHSZ	DEPINC fishsz tlevel blsec	prob4 fishsz
Total r^2	0·67	0·74	0·57	0·67	0·41	0·58

[a] Capitalized input parameters indicate partial correlations greater than 0·20.
Abbreviations: DPOWER–diffusion around mean migration direction; BLSEC–swimming speed; PROB3–historical probability of occurrence in offshore zone containing locus of oil spill; OILUP–rate of uptake of oil to muscle; ANGLE–mean angle of migration; PPBOIL–concentration of oil; XCON–mean concentration of oil experienced in last 24 h; FISHSZ–size of fish; TLEVEL–concentration of oil in tissues that causes tainting; FUELUP–increase in effects of fuel oil vs crude oil; AVOID–probability of avoidance of oil; DEPINC–increase in depuration with time; PROB4–historical probability of occurrence in offshore zone adjacent to locus of oil spill.

Throughout these simulations the sockeye salmon have been considered in isolation from other species which might interact with them as prey or predators. In the short term, response of prey populations did not appear important because the evidence suggested that the salmon would stop feeding at oil concentrations below those at which prey populations would be expected to change. Predator response to the polluted water may be a more significant effect. The sockeye salmon returning to the Kvichak and Nushagak rivers have no choice but to eventually enter through the bays where Frost *et al.* (1983) estimated that 1100 belukha whales were present during smolt outmigration in 1983. The belukhas' major prey from late May to early June is the sockeye salmon smolt, and from mid-June to mid-August the adult sockeye salmon. The above authors estimated that in Kvichak Bay in 1983 the belukhas consumed about 280 000 adults, which comprises 1%

of commercial sockeye salmon catch and 9% of the catch of other salmon species. Substantial numbers of other marine mammals can also be expected to prey on returning salmon. Oil pollution could affect short-term feeding behaviour and distribution and, over the long term, could adversely affect resident populations.

Predatory pressure exerted by the commercial salmon fishing fleet would very likely change following an oil spill. Tainting in only a small proportion of the overall returns would pre-empt most fishing due to adverse consumer perceptions. Following the 'Drupa' oil spill, saithe in seine nets contaminated with crude oil were wanted for neither animal nor human consumption, even though organoleptic analysis indicated an absence of tainting in the flesh (Grahl-Nielsen *et al.*, 1976). Initially, any reduction in mortality of the returning adults or emigrating juveniles would appear beneficial to the salmon population. However, Solomon & Mills (1982) suggested that lack of fishing could result in escapements of salmon more numerous than the spawning areas could support (overescapement) with consequent nest superimposition, loss or damage of eggs, and increased probabilities of infectious disease (i.e. a 'Ricker-type' stock and recruitment relationship). If overescapement is to apply it needs to be demonstrated that a reduction in juvenile production occurs at higher spawner densities. Rogers (1984) provides mean spawner densities and the resulting adult returns per spawner for six Bristol Bay sockeye salmon stocks (Kvichak, Naknek, Egegik, Ugashik, Wood and Igushik) from 1952 to 1983. Mean spawner numbers ranged from approximately 270 to 5400 spawner per square kilometer of lake area. The ratio of returning adults to spawners ranged from approximately 0·45 to 7·4. Using Rogers' (1984, his Fig. 14) data, the natural log of returning adults (R) plotted against the natural log of spawner per square kilometer (S) gives a slope of greater than 1·0 ($R = 47{\cdot}35S^{1{\cdot}74}$, $n = 32$, $0{\cdot}01 > p > 0{\cdot}005$). Thus, over this range of spawner densities, there was no indication of declining returns, or even declining percentage returns, at the higher spawner densities. Reductions in recruitment might be observed at greater spawner densities (i.e. the above data fall only on the ascending limb of a 'Ricker-type' recruitment curve); however, exploitation rates of the returning Bristol Bay sockeye salmon (47% from 1951 to 1960, 48% from 1961 to 1970, 21% from 1971 to 1976 (Rogers, 1977)) are such that even a complete cessation of fishing would, at most, double the escapement which, for 27 out of the 32 years from 1952 to 1983, would still have produced an escapement less than the maximum recorded escapement over the same period. Thus it appears unlikely that on a system-wide basis 'overescapement' is of concern in the Bristol Bay rivers; individual rivers could, of course, show a different trend than the mean.

Finally, the results of this study depend on the distance of the oil spill from shore. An inshore spill would affect the returning adults more than an offshore spill, especially if the oil entered the inlets where large numbers of salmon would typically collect before ascending the rivers.

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